A Search for γ Doradus-Type Variable Stars in the Hyades

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ABSTRACT
γ Doradus stars are photometrically variable early F-type stars on or just above the main sequence in the Hertzsprung-Russell Diagram. They vary by as much as 0.1 mag on time scales an order of magnitude slower than the fundamental radial pulsation period. These brightness variations are presumably due to non-radial gravity-mode pulsations. We obtained high precision V-band photometry of 8 F0 to F5 stars in the Hyades (BS 1319, BS 1354, BS 1385, BS 1408, BS 1430, BS 1432, BS 1459, and BS 1472) and found that none of them showed strong evidence of γ Dor-type variability. Since γ Dor-type candidates are found in the Pleiades and in NGC 2516 (having ages of 78 and 137 Myr, repectively) but apparently not in the Hyades (age > 600 Myr), we hypothesize that the γ Dor phenomenon is a characteristic of relatively young F stars.

Two of the stars investigated showed marginal evidence of low-amplitude variability. The ±3 mmag variability of the F5 star BS 1319 is most likely due to rotational modulation of star spots, though it is not impossible that it is a γ Dor star. Another F5 star BS 1459 ($\Delta V = \pm 2$ mmag) has a possible period similar to δ Scuti stars, but no firm conclusions should be made concerning its behavior unless and until its variability is confirmed.

Key words: Stars: pulsation – Stars: spotted – Stars: variables.

1 INTRODUCTION

δ Scuti stars, SX Phoenicis stars, and γ Doradus stars are three kinds of pulsating variable stars of similar spectral type and luminosity class. All three types are found near the main sequence in (or near) the Cepheid instability strip in the Hertzsprung-Russell (HR) Diagram.

δ Scuti stars comprise the largest class of these three types of stars (Breger 1979, Rodriguez et al. 1994), and are subsequently the best studied. They typically have photometric periods of 1–3 h, low photometric amplitudes (0.02 mag), and have metal abundances and space motions typical of Population I stars.

SX Phoenicis stars have similar periods but typically have much higher photometric amplitudes (0.3 to 0.8 mag). They have metal abundances and space motions typical of Population II stars, and are blue stragglers in the post-main sequence stage of evolution. (See Garcia et al. 1990; Kim, McNamara & Christensen 1993.)

γ Doradus stars are the most recently identified of the three types of variable stars just mentioned. They are typically early-F stars on, or just above, the main sequence in the HR Diagram, and they are at or beyond the cool edge of the Cepheid instability strip. They exhibit photometric

variability as large as 0.1 mag in V on a time scale of 0.5 to 3 d. At the time of this writing there were 17 known candidates of this type (Krisciunas & Handler 1995). The best studied examples are γ Doradus itself (Balona, Krisciunas & Cousins 1994), 9 Aurigae (Krisciunas et al. 1995a), HD 224638 and HD 224945 (Mantegazza, Poretti & Zerbi 1994).

δ Scuti stars and SX Phoenicis stars are believed to exhibit radial pulsations (in the fundamental mode), radial overtones, and non-radial pressure mode (p-mode) oscillations. Recently, Breger (1993) has shown that some δ Scuti stars also show evidence of lower frequency (longer period) variations, which one would attribute to non-radial gravity mode (g-mode) pulsations. Amongst γ Doradus stars, γ Dor and 9 Aur have photometric periods, radial velocity variations, and line profile variations consistent with the notion that they are exhibiting g-mode pulsations. Recently, Aerts & Krisciunas (1995) have found that 9 Aur can be modelled as an $\ell = 3, |m| = 1$ non-radial pulsator.

An interesting question one might pose is: how is the pulsational behavior outlined above related to the age of A- and F-type stars? We know that SX Phe stars are "old", typically 1–2 Gyr for a mass of 1.6 $M_\odot$ (Rodriguez, Rolland & Lopez de Coca 1990). γ Dor itself is imbedded in a β Pictoris-type disk or envelope (Walker & Wolsten-

croft 1988), and so is presumably "young". Antonello and Mantegazza (1986) found four "slowly" varying F stars in the cluster NGC 2516. Mantegazza (private communication) indicates that subsequent unpublished photometry of this cluster revealed other candidates. The main sequence turnoff point for NGC 2516 corresponds to a spectral type of a late-B star, so its age should be comparable to the Pleiades (i.e. 78 Myr; Lang 1992). We note that the Pleiades itself has one γ Dor candidate, HD 23375 (Breger 1972).

It would be interesting to determine if γ Dor stars, δ Scuti stars and SX Phe stars are to be found only in certain ranges of age. Since we know of only a relatively small number of γ Dor stars, it would also be useful to increase the number of known candidates. In this paper we report our attempts to identify γ Dor stars in the Hyades, the age of which is 661 Myr (Lang 1992).

2   OBSERVATIONS

We chose stars in the Hyades from Welch's (1979) list and considered information given in the The Bright Star Catalogue (Hoffleit & Jaschek 1982). Known δ Scuti stars were avoided. This left us with 8 early- to mid-F stars. To our knowledge none of these 8 stars has ever been checked carefully for variability on the time scale we are interested in here. However, we note that three of our stars (BS 1430, 1432, and 1472) were observed by Horan (1979) in his search for δ Scuti stars in the Hyades. From 3 to 4 hours of monitoring, he found that each of these three stars was constant to 3 mmag or better. In order to find out if any of these stars showed γ Dor-like variability, observations over longer time scales were still warranted.

Our observations were principally made with the 0.6-m reflector at Mauna Kea, Hawaii, using an Optec SSP-5 photometer owned by the University of Hawaii at Hilo. Other measurements were made by one of us (KK) at Cerro Tololo, Chile, using the 0.6-m Lowell telescope, a dry ice cooled photomultiplier tube in the ASCAP photometer, and a 4.5 mag neutral density filter. Luedeke's data were obtained with his 0.25-m reflector in Albuquerque, New Mexico, and an Optec SSP-3 photometer. Appropriate V-band differential extinctions corrections were made with values of the extinction derived nightly. Transformation to the UBV photometric system was accomplished with observations of red-blue pairs of known brightness and color (Hall 1983).

The Mauna Kea and Cerro Tololo data were taken in the following manner: comparison star – two program stars – comparison star – two other program stars – comparison star, etc. One cycle on the 8 program stars, bracketed by 5 measures of the comparison star, took between 35 and 50 minutes. (This was mostly owing to the constraint of having to set the telescope manually.) Each measure of a star actually consisted of two consecutive 30 second integrations. If these two measures were not within one percent, we often found that the star was no longer centered in the diaphragm, or the seeing had gone bad, or the dome slit was in the way. Then a third or a fourth 30 second integration was taken.

We used BS 1422 (=vB 80) as our comparison star. It is a spectroscopic binary comprised of an F0V and a G2V star. This comparison star was suggested by Handler (private communication), who used it for over 100 h of pho-

Table 1. Summary of differential photometry of Hyades stars. The comparison star in all cases was BS 1422 (= vB 80; $V = 5.58$, $B–V = 0.32$). For each star we give the catalogue number from The Bright Star Catalogue, the corresponding number in van Bueren's (1952) list, the spectral type, the mean differential V magnitude, the internal error of a single differential value (i.e. the standard deviation of the distribution, *not* the mean error of the mean) the number of nights on which data were taken, and the number of data points.

BS	vB	Sp	$< \Delta V >$	σ(mmag)	N	n
1319	20	F5V	0.7410	3.7	20	76
1354	32	F3 : V	0.5372	5.1	18	45
1385	53	F4V	0.4094	4.5	18	44
1408	68	F0IV	0.3362	3.2	19	60
1430	84	F0V	-0.1639	3.5	18	45
1432	89	F4V	0.4397	4.0	18	45
1459	100	F5IV	0.4482	3.7	20	102
1472	103	F0V	0.2180	3.5	19	61

tometry in another photometric project. Given that many of the Hyades program stars proved to be constant within the errors of observation (see below), the choice of BS 1422 as the comparison star turned out to be an excellent one.

In Table 1 we give a summary of the V-band photometry, which was obtained from 1994 November 15 to 1995 January 23 UT. Typically, an individual differential magnitude obtained with the 0.6-m telescopes had an internal error of $\pm$ 4 mmag. For Luedeke's data a typical individual measure is good to $\pm$ 10 mmag. To equalize the weighting for subsequent analysis, each of Luedeke's data points represents the mean of three differential measures. The data can be obtained from IAU Commission 27 as file 302E of unpublished photometry. (See Breger, Jaschek & Dubois 1990 for further information.)

The reader will notice that the average number of data points obtained per night (per star) was small. If any of the stars listed in Table 1 were photometrically variable in the manner of γ Dor or 9 Aur, they would easily have flagged themselves as "stars worthy of further investigation". We assert this on the basis of actual photometry of γ Dor and 9 Aur obtained during the 10-night observing run at Cerro Tololo and the 7-night observing run at Mauna Kea. We took subsets of photometry of γ Dor and 9 Aur, amounting to 4 points per night. The range of the data in both cases was nearly 0.08 mag (giving evidence of variability at the 15-σ level or better). Power spectra of these subsets of data revealed the principal frequency plus some aliases. False alarm probabilities of the highest peaks in the power spectra of such subsets of data ranged from 3×10^{-4} to 4×10^{-3}.

It was our expectation that some of the Hyades stars would turn out to be very constant.[*] That would give us

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[*] It could be argued that a star is either "constant" or "variable" and cannot be "very constant" or "somewhat constant". However, it is easier to determine that a variable star is variable than to prove that a constant star is constant, because in the latter case one must cover all reasonable time scales, from minutes to years, and one always has to deal with photon statistics. Here we define a *constant* star to be: (1) one that shows very little range in the data values (i.e. ± 2-σ, where σ is the typical internal error of a single differential measurement; and (2) one for which the power

an estimate of the accuracy of the photometry. If any of the 8 Hyades stars were found to be constant with respect to BS 1422, then we would know that BS 1422 is a "safe" comparison star. Suspected variability of another star, observed differentially with respect to BS 1422, would be safely attributed to the program star.

3 ANALYSIS OF PHOTOMETRY

Our principal tool for the analysis of the photometry was to produce power spectra, using the Lomb-Scargle algorithm as presented by Press & Teukolsky (1988). Typically, we chose an oversampling factor of 4 and calculated the power spectra to a frequency two times the Nyquist frequency (HIFAC = 2). It is allowable to investigate frequencies beyond the Nyquist frequency if one has unequally sampled data, as is always the case with astronomical photometry carried out over a number of days primarily at a single site. Indeed, in the case of the low-amplitude ellipsoidal star BS 1568, observations by Guinan and McCook from 1989/90 reveal the true frequency of variability only if one calculates the power spectrum to 2.3 times the Nyquist frequency (Krisciunas et al. 1995b).

One of the parameters obtained from the analysis is the false alarm probability of any given peak in the power spectrum. This is the probability that a *random* sample would give a peak of a given height. Large data sets on periodically variable stars such as γ Dor give vanishingly small false alarm probabilities (e.g. 10^{-20}). False alarm probabilities of 0.01 are usually significant.

To refine the value of the frequency of a peak indicated by the power spectrum, we used the multiple period determination program PERDET (Breger 1989). This also allowed a least-squares determination of the amplitude and phase of the sinusoid.

During our 10 night observing run (1994 November) at Cerro Tololo as part of a multi-longitude campaign on γ Dor, we observed each of stars in Table 1 a total of 17 times when the Hyades was near the meridian. Luedeke also observed all 8 stars on one night just prior, and one night just after, the CTIO observations. Clearly, the Hyades cluster is not well placed for observations at 30 degrees south latitude, but on the basis of this small amount of data we already knew that the Hyades F-type stars were constant to ±0.01 mag or better.

Mauna Kea is at an ideal latitude for Hyades observations. Over the course of a 7 night multi-longitude campaign

spectrum of the photometry shows no significant peaks. The definition of "significant peak" must be left somewhat vague, because it depends on the mechanism of variability of a star and the coherency argument relating to the reality of a given frequency. For example, we recently found that the star 7 Cam (= BS 1568) is a low-amplitude (±6 mmag), photometrically variable, ellipsoidal star. (It was observed during the 7 night run at Mauna Kea, during which most of the data of this paper were obtained.) The only significant peak in the power spectrum of its photometry corresponds to half the orbital period of the star about its unseen companion. (See Krisciunas et al. 1995b.) In this paper we will argue for the significance of one peak in the power spectrum of the photometry of BS 1319, owing to its projected rotational velocity.

on 9 Aur (the northern prototypical γ Dor star), we observed the Hyades stars again and obtained typically 4 points per night. (Except for New Year's Eve, when we were hampered by winds, the observing conditions were excellent.) As mentioned above, if any of these stars were exhibiting γ Dor-type activity, that would have been revealed.

Fig 1 shows an altogether uninteresting power spectrum of the BS 1385 vs. BS 1422 data obtained at Mauna Kea. The largest peak in the power spectrum gives a false alarm probability of 0.78. There is clearly no evidence of periodic variability.

From the internal errors listed in column 5 of Table 1 and power spectra such as that shown in Fig 1 we conclude that the following stars exhibit no evidence of variability: BS 1354, BS 1385, BS 1408, BS 1430, BS 1432, and BS 1472.

Power spectra of the photometry of BS 1319 and BS 1459 gave hints that they might be low-amplitude variables. In the case of BS 1319 the suggested period was 1.4 d. In the case of BS 1459 the suggested period was in the range 3–5 h.

On the nights of 1995 January 22 and 23 UT we concentrated our efforts on these two stars, obtaining 57 points on BS 1319 and 31 points on BS 1459. The comparison star once again was BS 1422. BS 1408 was used as the check star on January 22. BS 1472 was used as the check star on January 23.

Fig 2 shows the power spectrum of all the available data on BS 1319 (1994 November 15 to 1995 January 23 UT). We believe that $f = 0.6976$ d^{-1} is a true frequency. (The other peak would simply be its one-day alias). The false alarm probability of this peak is 0.02.

Fig 3 shows all the available BS 1319 data folded with a period of $1/f = 1.4336$ d. The sinusoid shown has an amplitude of 3.0 mmag. That amplitude has a 1-σ error of ±0.5 mmag.

Fig 4 shows the power spectrum of the BS 1459 vs. BS 1422 data obtained on the nights of 1995 January 22 and 23 UT. The false alarm probability of the highest peak in the power spectrum is 0.28.

Fig 5 shows the photometry of BS 1459 vs. BS 1422 obtained on 1995 January 22 and 23 UT, folded with a period of 0.1670 d. The sinusoid shown has an amplitude of 1.8 mmag. That amplitude has a 1-σ error of ±0.5 mmag.

4 TWO LOW-AMPLITUDE VARIABLES?

We believe BS 1319 to be variable at the ±3 mmag level, and we believe this to be due to rotational modulation. We have calculated the radius of the star using Strömgren photometry (Hauck and Mermilliod 1990) as input. The star's absolute magnitude and radius are calculated by means of relationships given by Balona & Shobbrook (1984) and Moon (1984). The resulting size of the star is 1.53 R$_\odot$. Given its projected rotational velocity of $v \sin i = 53$ km sec^{-1} (Hoffleit & Jaschek 1982), the derived rotational period is 1.46 d times sin i. If we are looking at the star side-on ($i \approx 90°$), this closely approximates the period of 1.4336 d obtained from the photometry.

Because of the near coincidence of the corresponding period of one of the two peaks in the power spectrum given in Fig 2 with the maximum allowed rotational period of

Figure 1. Power spectrum of the *V*-band photometry of BS 1385 vs. BS 1422, obtained at Mauna Kea from 1995 December 29 to 1995 January 4 UT.

Figure 2. Power spectrum of all available photometry of BS 1319 vs. BS 1422 (1994 November 15 to 1995 January 23 UT).

the star, the simplest explanation for the variability of BS 1319 would be rotational modulation, presumably of star spots. Now, it is generally believed that stars with spectral types earlier than F7 do not show evidence of star spots (Giampapa and Rosner 1984). However, Güdel, Schmitt & Benz (1995) report the surprising result that the F0V star 47 Cas exhibits evidence for strong coronal activity. Spotted stars often have enhanced coronal activity. The kind of vari-

ability hinted at in our photometry of BS 1319 is two orders of magnitude less than that found on some spotted stars.

While the coherency argument favors the star spot hypothesis for the variability, it is *possible* that the BS 1319 is a γ Dor-type star. To prove this would require extensive and highly accurate photometry carried out during a multi-site campaign. One would be looking for evidence of multiple periods, as are found in other γ Dor candidates. Given the

Figure 3. All available photometry of BS 1319 vs. BS 1422, folded with a period of 1.4336 d.

Figure 4. Power spectrum of BS 1459 vs. BS 1422 photometry obtained at Mauna Kea on 1995 January 22 and 23 UT.

small photometric range of BS 1319 ($\Delta V < 0.01$ mag vs. $\approx$ 0.1 mag for 9 Aur and γ Dor), the other signatures of pulsation such as radial velocity and line profiles changes would probably not be measurable.

Regarding BS 1459, it is *possible* that it is variable at the ± 2 mmag level, but demonstrating this convincingly is another matter. Given the relatively high false alarm probability of the highest peak in the power spectrum of Fig 4, and the low amplitude of the best sinusoid shown in Fig

5, we are not confident in saying that BS 1459 is definitely variable.

5 COMPARISON WITH KNOWN δ SCUTI STARS IN THE HYADES

Let us assume for the sake or argument that both BS 1319 and BS 1459 are pulsating. How do their pulsation constants compare to known δ Scuti stars in the Hyades?

Figure 5. BS 1459 vs. BS 1422 data obtained on 1995 January 22 and 23 UT. The data have been folded with a period of 0.1670 d.

Rodriguez et al. (1994) give an extensive catalogue of δ Scuti stars, 8 of which (BS 1351, 1356, 1368, 1392, 1394, 1412, 1444, and 1547) are in the Hyades. We have calculated the pulsation constants Q from the equation given by Breger & Bregman (1975):

$$\log Q = -6.454 + \log P + 0.5 \log g + 0.1\ M_{bol} + \log T_{eff}. \quad (1)$$

Values of $\log g$ and T_{eff} were calculated from the Strömgren photometry given by Rodriguez et al. (1994) and software based on Moon & Dworetsky (1985). The absolute visual magnitudes were also calculated from the Strömgren photometry, rather than from the apparent magnitudes, slight reddening corrections, and the Hyades distance modulus. We adopted a bolometric correction for stars of this spectral type of -0.10 (Harris 1963).

In Fig 6 we plot a color-magnitude diagram containing 16 of the 17 γ Dor candidates given by Krisciunas & Handler (1995), the 8 δ Scuti stars in the Hyades, and the two low-amplitude variables from this paper. We note that the bona fide γ Dor stars (plotted as circles in Fig 6) are found in a very small region of the diagram, near the intersection of the cool edge of the instability strip and the main sequence, while the δ Scuti stars are distributed throughout the instability strip.

For the 8 δ Scuti stars we find $0.016 < Q < 0.031$ d. The larger values of Q are consistent with these stars exhibiting pulsation in the fundamental radial mode or in the first radial overtone, while the smaller values of Q might correspond to higher radial overtones (Stellingwerf 1979). However, we would like to emphasize that *one cannot determine the pulsational mode of a star from the Q value alone. Too many non-radial modes are possible.*

We carried out the analogous calculations for BS 1319 and BS 1459 using Strömgren photometry from Hauck & Mermilliod (1990). The bolometric correction for F5 V stars

is -0.04 (Harris 1963). For BS 1319 we find $Q = 0.965$ d. Stars pulsating in the fundamental radial mode can have Q values as high as 0.12 d (Cox 1980). *If* BS 1319 is pulsating, it must be exhibiting non-radial g-modes.

If $f = 6.0$ d^{-1} is a true frequency of pulsation for BS 1459, its pulsation constant is $Q = 0.113$ d. If $f = 18.0$ d^{-1} is instead a true frequency of pulsation (see Fig 4), then $Q = 0.037$ d, and BS 1459 might possibly be a δ Scuti star. Given that BS 1459 lies far outside the cool edge of the Cepheid instability strip, this would indeed be remarkable. No firm conclusions should be made concerning its behavior unless and until its variability is confirmed.

6   DISCUSSION

We have shown that the stars BS 1354, BS 1385, BS 1408, BS 1430, BS 1432, and BS 1472 in the Hyades cluster are, for all intents and purposes, constant in brightness. BS 1459 might be photometrically variable at the ± 2 mmag level, but it is likely constant as well. These seven stars, along with the comparison star we used, BS 1422, can be considered excellent photometric standards.

Since some γ Dor stars are found outside the cool edge of the Cepheid instability strip in the HR Diagram, it could be that BS 1319 is a low-amplitude γ Dor star. However, the near coincidence of the photometric period and the upper limit to the rotational period would favor the explanation that its variability is due to star spots.

We have provided some evidence that BS 1459 might be a low-amplitude δ Scuti star, but we consider this an unlikely possibility. The variability of BS 1459 should be confirmed before any strong claims are made along these lines.

To substantiate the tentative conclusions obtained here concerning the variability of BS 1319 and BS 1459 would require much more extensive photometric monitoring of com-

Figure 6. A color-magnitude diagram for stars discussed in this paper. Circles: bona fide γ Dor stars from Krisciunas & Handler (1995). Triangles: γ Dor candidates in NGC 2516. Dots: other γ Dor candidates given by Krisciunas & Handler (1995). Squares: δ Scuti stars listed by Rodriguez et al. (1994). Asterisk: BS 1459. Five pointed star: BS 1319. The zero age main sequence is adopted from Crawford (1975, 1979), while the borders of the Cepheid instability strip are taken from Breger (1979).

parably high precision. In the case of BS 1319 multi-site photometry would be required to avoid aliasing in the power spectrum. BS 1459 might be adequately studied from a single site, given its much shorter implied period.

The most important result of this paper is that we find no early-F stars in the Hyades that clearly exhibit behavior like γ Dor, 9 Aur, HD 224638 and HD 224945. γ Dor itself is presumably a young object, since it is imbedded in a β Pictoris-like disk or envelope (Walker & Wolstencroft 1988). The Pleiades (having age $\approx$ 78 Myr; Lang 1992) contains 4 δ Scuti stars listed by Rodriguez et al. (1994) and one γ Dor candidate (Breger 1972; Krisciunas & Handler 1995). The cluster NGC 2516 contains a number of δ Scuti stars and also a number of γ Dor candidates. Snowden (1975) claims that NGC 2516 has an age of 137 Myr, or in any case is more evolved than the Pleiades. The Hyades (age > 600 Myr) contains 8 δ Scuti stars, but apparently no γ Dor stars. Present evidence lets us hypothesize that the γ Dor phenomenon is a characteristic of young F-type stars. Strong evidence of this will require many new observations and also theoretical breakthroughs.

NOTE ADDED IN PRESS

Eggen (1995) has independently suggested that the γ Doradus phenomenon is a characteristic of *young* F stars. He claims that γ Dor itself is part of the IC 2391 supercluster, with an age of 50 Myr. BS 8799, another γ Dor candidate, is a member of the Pleiades supercluster. He claims that HD 164615 and 9 Aur are young disk stars, owing to their space velocities. HD 224638 and HD 224945 have very small proper motions, characteristic of young disk stars. All these stars are to be found in the "Böhm-Vitense decrement", a gap in the color- magnitude diagram of cluster stars. Stars which have *not yet* undergone the abrupt onset of stellar convection, presumably younger stars, are to be found in this gap.

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